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The LHC Lattice, Version 4.

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Abstract

A preliminary four-fold symmetrical thick lens issue of the Version 4 of the LHC is described. This document details the design of the arc cell, the odd and even type arcs and experimental insertions. Specificity of the closed ring with 4-fold periodicity built up from these fragments is addressed. Description of tune split modes for coupling compensation, by method of arc tune split or phase trombone are presented.

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1. INTRODUCTION

A preliminary issue of the Version 4 of the LHC is presented. It is a four-fold symmetrical design of the lattice based on two types of low-β insertions, namely of the odd and even types, and correlatively two types of arcs, following the nomenclature of the previous Version 1 (Pink Book, [1]), Version 2 (White Book, [2]) and Version 3 [3] of the LHC.

Except for what will be described explicitly in the report, the arguments developed in the design studies of the previous Versions 1 to 3 are still valid and adapted to the new layout. The specificity of the Version 4 of the LHC lies in the 14.2 meters long dipole [4] (compared to 9 m in Version 1, 13.145 m in Version 2 and 15.574 in Version 3). The other major characteristics are the 6 dipoles per cell, the 23 cells per arc, and the dense packing of the dipoles in the regular cells, giving an increase of the magnetic length of 8.9% with respect to the preliminary Version 1 (which has eight dipoles per cell, 25 cells per arc), 3.5% with respect to the Version 2 (six dipoles per cell, 24 cells per arc), and a decrease of 0.1% with respect to the Version 3 (six dipoles per cell, 21 cells per arc). The field at the nominal energy of 7 TeV is 8.35 T, compared to 9.09 T in Version 1, 8.65 T in Version 2 and 8.34 T in Version 3. The maximum possible energy corresponding to a field of 9 T is 7.54 TeV, identical to Version 3, compared to 7.285 in Version 2. The machine tunes considered in this work are $Q_x = 66.28$ and $Q_y = 66.31$.

The present document details the design of the arc cell, the arcs and experimental insertions. Specificity of the closed ring with 4-fold periodicity built up from these fragments are addressed. Detailed studies on tune split modes for coupling compensation, by methods of arc tune split or phase trombone are presented. Provision is made on methods for switching from inner to outer injection schemes.

2. GENERAL LAYOUT

The geometrical parameters of the constitutive parts of the ring are gathered in **Table 1**. The ring is shown schematically in **Fig. 1**. It has an even number of crossing points for preserving identical circumferences of the two rings, following the scheme (3.b) stated in **ref.** [5]: two clusters of two consecutive non-crossing insertions each separated by three (namely here, IR 1,2 and 8) and one (namely IR 5) crossing insertions.

The geometry of the LEP and LHC rings cannot be the same in the dispersion suppressors, since the space is not sufficient for the *strong* quadrupoles required. Thus, the separation between the LHC and LEP footprints in the LEP tunnel is minimized by optimizing the dipole positions in the LHC dispersion suppressor [6], with the constraints of identical lengths for the two rings, and exact superposition of the interaction points (IP). This results in a maximum deviation of about 10.5 10^{-2} m at the level of the dispersion suppressor, 1.8 10^{-2} m in the arcs, and zero all along the interaction region (**Fig. 2**).

In what follows, the injection is assumed to be from inward, and hence the *inner* quadrupole Q10 of the even insertion regions (IR) is of the focusing type. However, provision is made in the section, for allowing to switch to an injection from outward, with a focusing *outer* quadrupole Q10 in the even insertion .

Table 1: Geometrical parameters of the Version 3 of the LHC ring

Total circumference	26658.863 m
Cell length	106.478 m
Cell curvature	30.478 10^{-3} rad
Number of cells per arc	23
Arc length	2446 m
Arc curvature	700.997 10^{-3} rad
Odd insertion length [1)]	885.631 m
Even insertion length	887.084 m
Odd LSS [2)] length	527.226 m
Even LSS length	528.238 m
Odd DS [3)] length	179.202 m
Even DS length	179.423 m
DS curvature	42.201 10^{-3} rad
The cell dipole:	
Length	14.2 m
Bending radius	2795.447 m
Curvature	5.0797 10^{-3} rad
Sagitta	9.016 10^{-3} m

[1)] Inclusive of Q10 and the residual drift 'S17' adjacent to the arc, at both ends
[2)] Long Straight Section. Inclusive of the outer triplets, up to the last DS dipole
[3)] Dispersion Suppressor

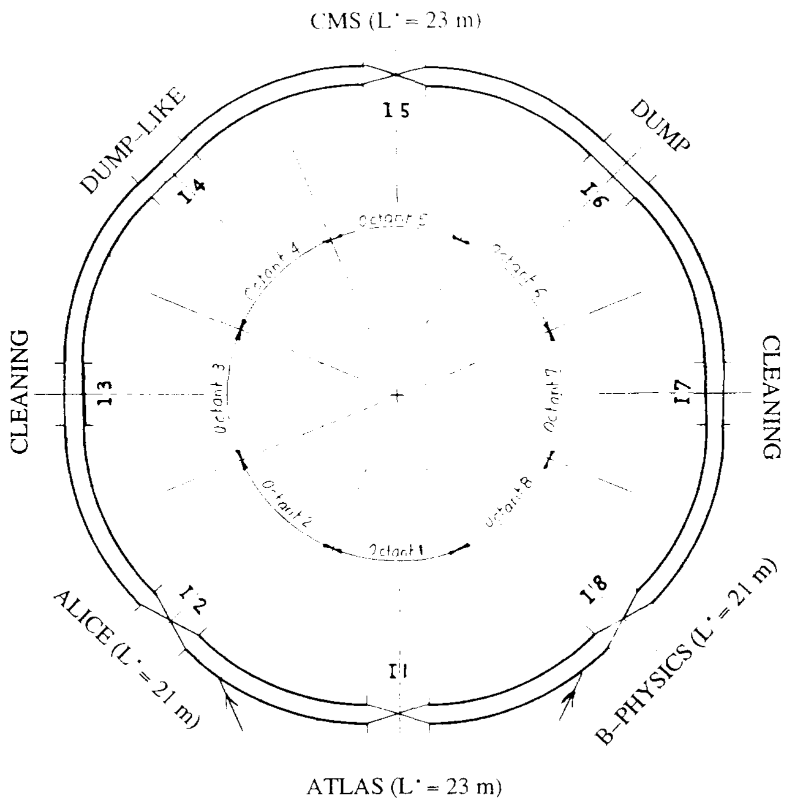


Fig. 1: A schematic layout of the Version 4 of the LHC ring

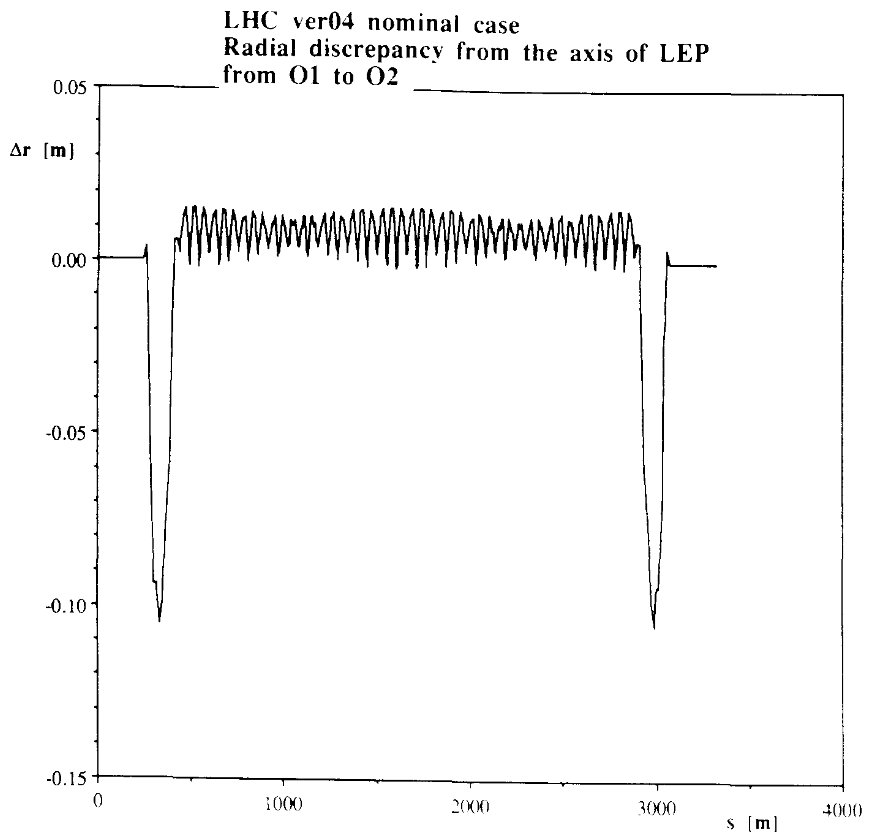


Fig.2: Radial difference between the LEP and LHC footprints in the LEP tunnel

3. CELL AND ARC

The nominal parameters of the normal cell can be found in **Table 2.** A scheme of the cell and its constitutive parts is displayed in **Fig. 3**.

Table 2: Parameters of the regular cell

Number of cells per arc	23
Cell length	106.478 m
Dipole[1)] length	14.2 m
Nominal/maximum energy	7 / 7.54 TeV
Field at nominal/maximum energy	8.35 / 9 T
Quadrupole[1)] length	3 m
Gradient for 90° at nominal energy	210 T/m
Tuning quadrupoles	none
Dipole/sextupole corrector strength	To be determined
Octupole/skew quadrupole length	To be determined

[1)] Dipoles and quadrupoles are powered independently of each other

Focusing

The **Fig. 3** shows the cell focusing, assuming betatron phase advances of 89.709^{O} - horizontal (Q_x = 0.24919) and 89.653^{O} - vertical (Q_y = .24903), obtained with $K_F = 9.0020\ 10^{-3}\ m^{-2}$ and $K_D = -8.9974\ 10^{-3}\ m^{-2}$ in the main F/D quadrupoles (i.e., a gradient of 210 T/m at the nominal energy of 7 TeV). This translates into arc tunes values of $Q_x = (66.28 - 8\times2.566) / 8 = 5.719$ and $Q_y = (66.31 - 8\times2.566) / 8 = 5.723$ (considering a phase advance of 2.566 in the insertion, in both planes). Hence, the total contribution of the arcs to the machine tune is 45.752(x)/45.782(y).

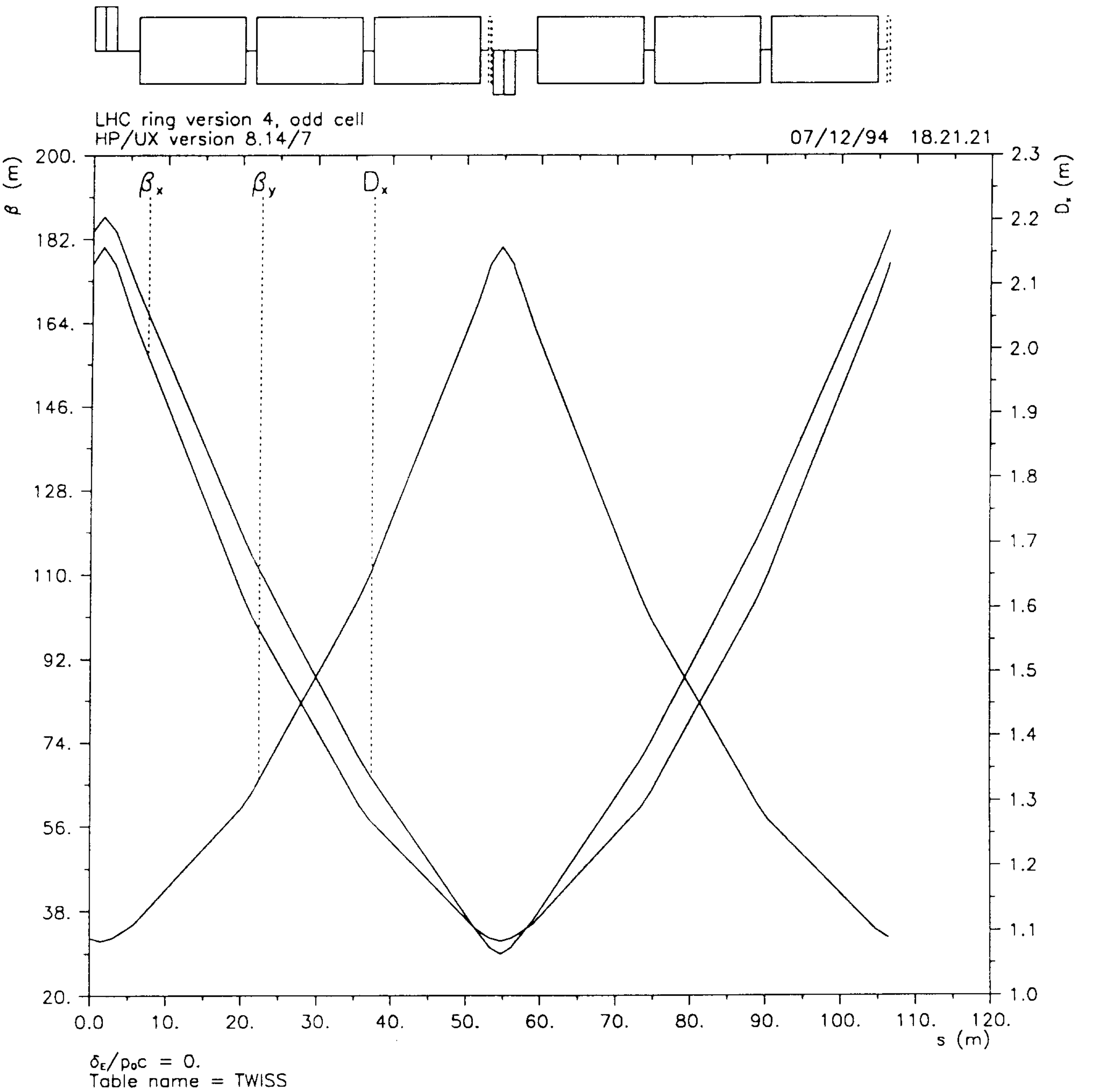


Fig. 3: Optical functions of the regular arc cell
maximum/minimum β : 176.71/32.33 m
maximum/minimum D_X: 2.18/1.10 m

4. DISPERSION SUPPRESSOR

The dispersion suppressor (DS), placed at both ends of the interaction regions and adjacent to the arcs, consists of 4 quasi-regular half-cells (**Fig. 4**) with quadrupoles numbered Q7 (on the interaction point side) to Q10 (on the arc side).

Each one of the three quadrupoles Q8 to Q10 are split in two parts: a main quadrupole (connected in series with the arc quadrupoles), and a tuning companion quadrupole (of maximum allowed gradient 120 T/m, powered independently). Q7 is made of a main part and two tuning companions. The quadrupole lengths are given in **Table 3**.

The focusing assures a phase advance of about π in both planes, small β changes in the outer triplet, and small changes of the tuning quadrupoles QT10, QT9, QT8, QT7, during the scan of β^* at the IP. The four half-cells contain a pair of dipoles of the regular type (14.2 m, curvature 5.0797 10^{-3} rad), and the Q9-Q8 half-cell contains in addition a short dipole (4.37 m, curvature 1.563 10^{-3} rad).

Table 3: Quadrupole lengths in the dispersion suppressor.

Main quadrupole	Magnetic length (m)	Companion tuning quadrupole	Magnetic length (m)
Q7	4.0	QT7[1)]	2.5
Q8	3.4	QT8	2.5
Q9	2.5	QT9	2.5
Q10	2.5	QT10	2.5

[1)] Two such tuning quadrupoles, companion of Q7.

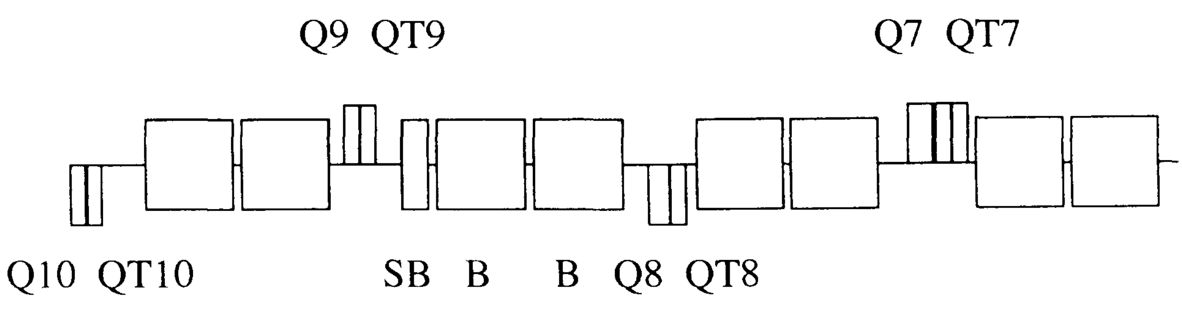


Fig. 4: Schematic layout of the dispersion suppressor

5. INSERTION

The odd and even types of insertion regions differ by the free space at the interaction point, namely, respectively L*=23 m and L*=21 m (**Fig. 1**). Both the odd and even types are built up from a long straight section (LSS), which contains, starting from the IP, the inner triplet (Q1-Q3) that focuses the beam at the IP, the separation-recombination dipole doublet (D1, D2) that assures the crossing angle between the two beams at the IP and their 0.18 10^{-2} m separation outwards, the outer triplet (Q4-Q6) for the β^* tuning at the IP, and the dispersion suppressor at the end, for cancellation of the dispersion and its derivative at the IP. The insertion is geometrically symmetrical with respect to the interaction point (IP), and optically antisymmetrical (opposite focusing strengths with respect to the IP). The lengths of the constitutive parts are given in **Table 1**.

The inner triplet (Q1-Q3) is made of split quadrupoles: Q1 and Q3 are split in a main quadrupole and a tuning quadrupole (respectively, QT1 and QT3), while Q2 is split into two identical parts connected in series. The lengths are given in **Table 4**.

The LSS separating superconducting dipoles D1 and D2 (both 10.2 m long, distance 35.7 m) provide identical deflections of 1.961 10^{-3} rad and opposite signs.

A schematic layout of the insertion is displayed in **Fig. 5**.

Table 4: Quadrupole lengths in the insertion region
(identical for both the odd and even insertion types).

Main Quadrupole	Magnetic length (m)	Companion tuning quadrupole	Magnetic length (m)
Q1	5.5	QT1	1.5
Q2[1)]	5.5		
Q3	5.5	QT3	1.5
Q4	4.0		
Q5	8.0		
Q6	8.0		

[1)] Two such quadrupoles.

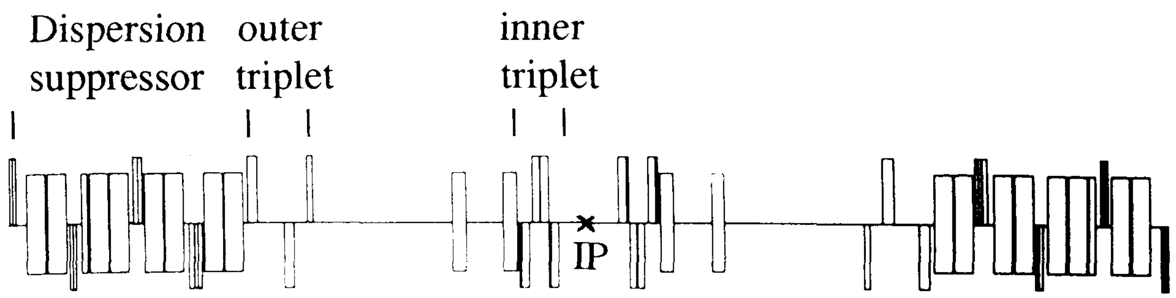


Fig. 5: Schematic layout of the interaction region

Tunability.

The β^* value at the IP can be scanned continuously over a range from 0.5 m (low β collision mode) to 11 m (high β collision mode) through 6 m (injection mode), with the same matching constraints as for the Version 1 of LHC (The Pink Book [1], page 33), while the phase advance in the insertion is requested to be constant and 2.566 in both planes. The resulting variations of the quadrupole strengths over the scanning range are displayed in **Fig. 6**, as a function of β^*. These curves show slight discontinuities at 6 m, which is an artefact that would have to be smoothed out, and corresponds to a discontinuous modification of the matching conditions: the constraint of zero D_x' (derivative of the dispersion) at the IP is replaced above $\beta^* = 6$ m, by the requirement of equal peak values of the β_x and β_y functions in the outer triplet.

The peak values of the β functions occur either in the inner triplet - for $\beta^* < 6$ m, or in the outer triplet - for $\beta^* > 6$ m (**Fig. 7**). The injection conditions are set close to this minimum value of $\beta^* = 6$ m, for optimizing the beam envelope in the insertion, with special emphasis on its size inside the inner triplet: the normalized emittance $\gamma\varepsilon/\pi$ (with $\varepsilon/\pi = 3.75\ 10^{-6}$ m.rad at 0.450 TeV) is in the ratio of the γ's, i.e., 450/7000, while the peak β values in the inner triplet are in a ratio of about 380/4420 in the odd insertion - L*=23 m (respectively 350/4000 in the even insertion - L*=21), which results in quasi identical beam envelopes $\sigma = \sqrt{(\beta\varepsilon/\pi)}$ in the inner triplet, at both injection and collision energies, namely, $\sigma_{col} / \sigma_{inj} \approx 0.86$ in both cases L*=23 m and L*=21 m.

The following **Figs. 8a-b, 9a-b** show the optical functions of the odd and even insertions, at both collision and injection conditions.

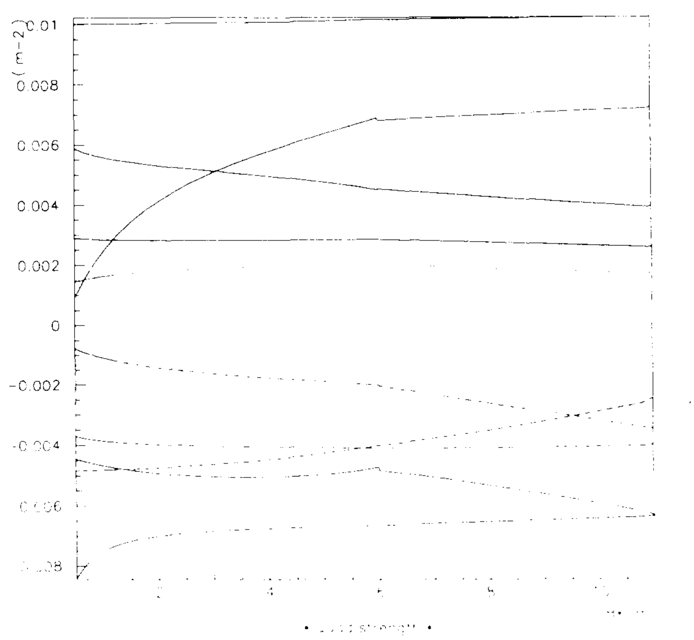
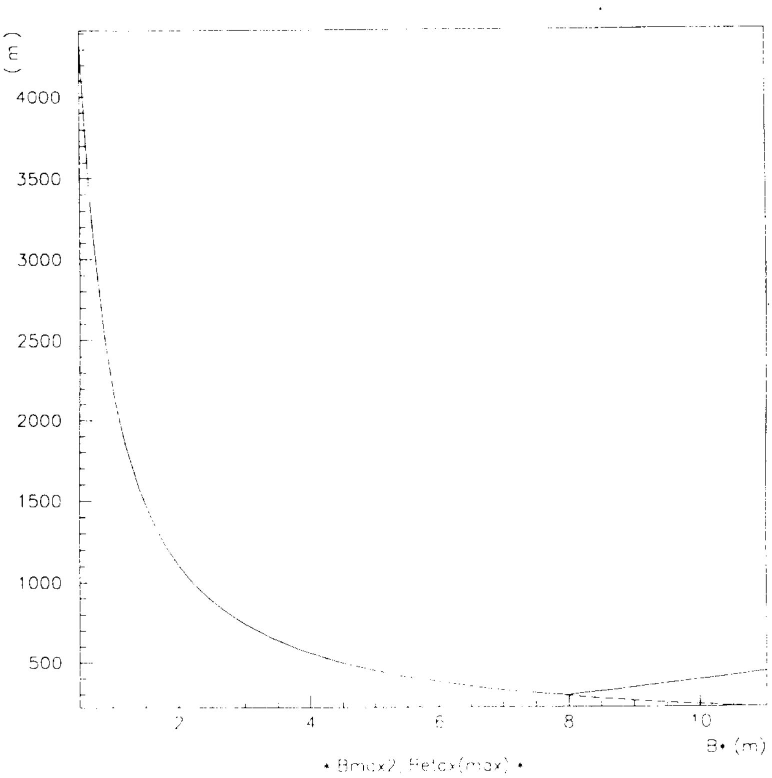


Fig. 6: Scan of the quadrupole strengths of the odd type insertion, over the range 0.5 m $\leq \beta^* \leq$ 11 m (similar results are obtained for the even type insertion)



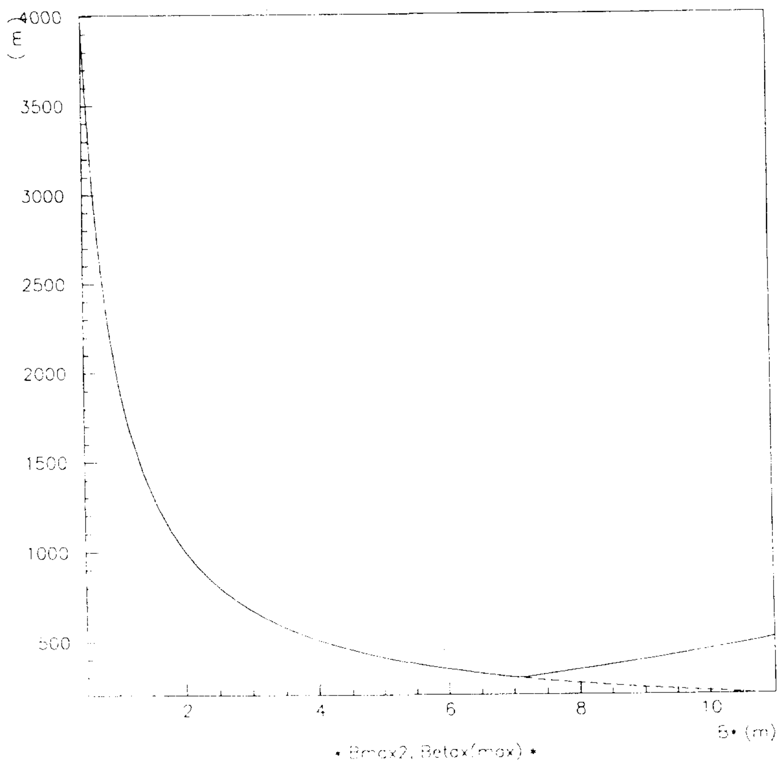
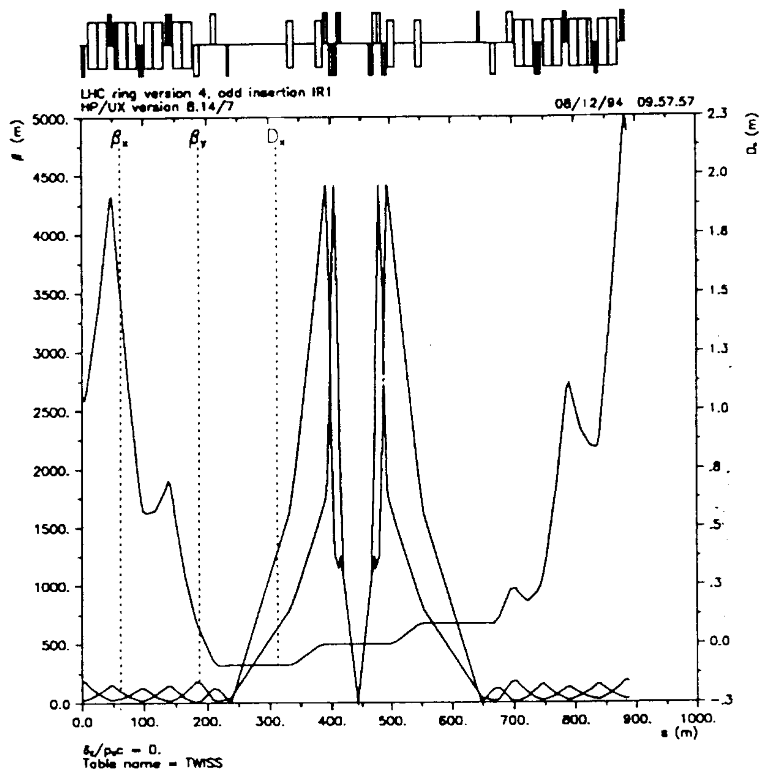


Fig. 7: Peak value of the β functions in the a) odd (L*=23 m) and b) even (L*=21 m) insertion, as a function of β*, over the range 0.5 m ≤ β* ≤ 11 m



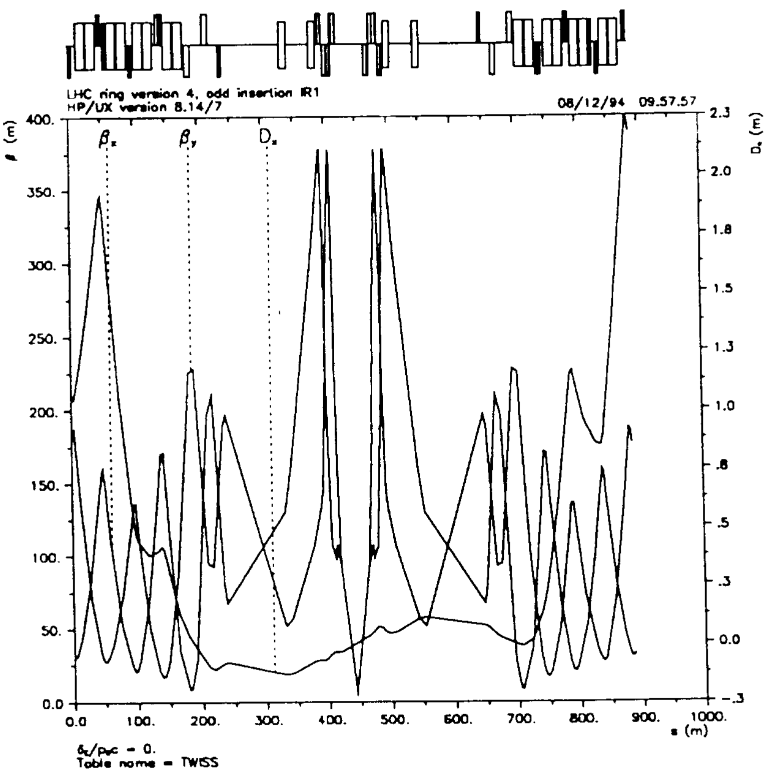
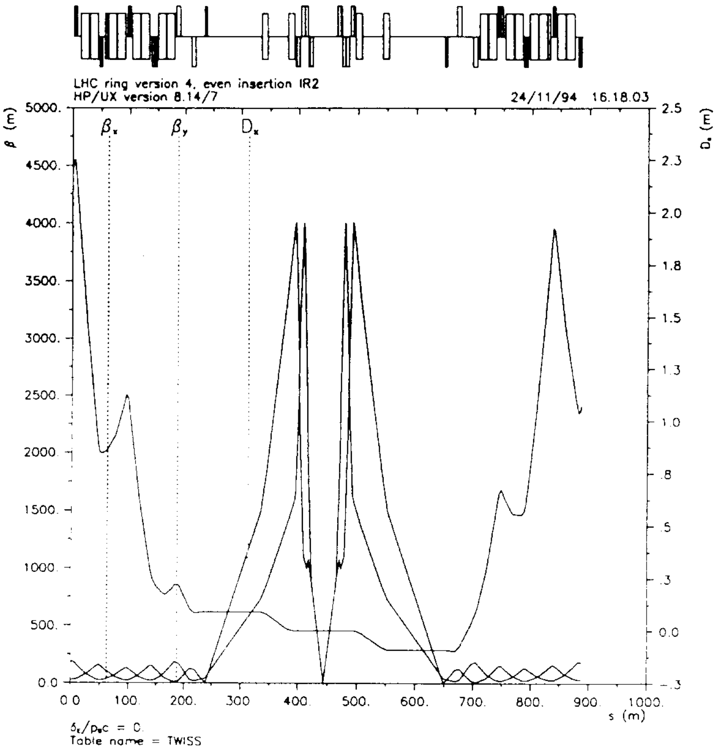


Fig. 8: Optical functions of the odd insertion (L*=23 m)
upper frame: collision conditions, β^* = 0.5 m
lower frame: injection conditions, β^* = 6 m



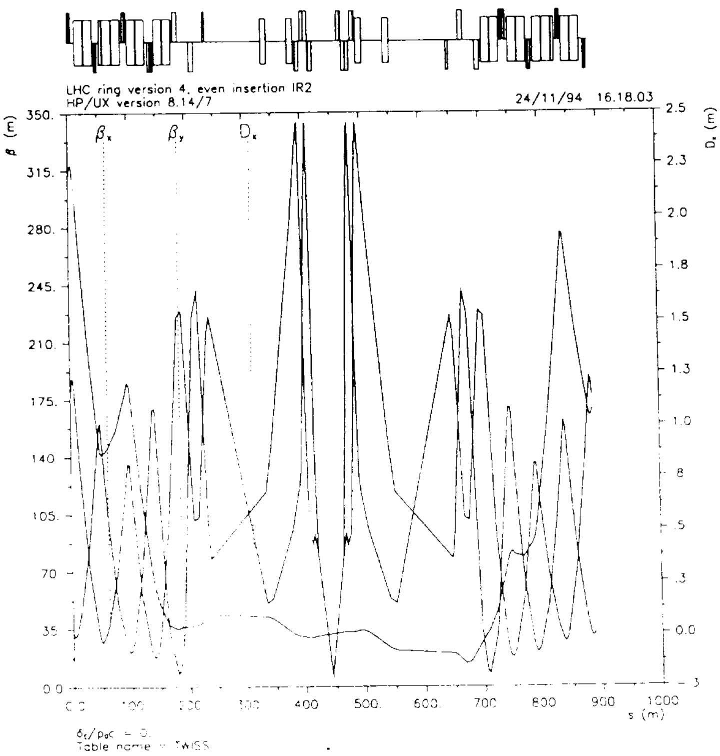


Fig. 9: Optical functions of the even insertion (L*=21 m)
upper frame: collision conditions, β* = 0.5 m
lower frame: at injection conditions, β* = 6 m

7. THE RING

A symmetric ring is built up from the various fragments described in the previous sections. The ring is 4-fold periodic, namely, assumed to be made of 8 experimental IR's, alternately of the odd and even type. However, prior to closing the full machine, a β matching between the arc and the insertion must be performed due to the difference between the real and theoretical arcs (in other words, due to the end half-quadrupoles of the arc belonging in the dispersion suppressors on both sides - quadrupole Q10, see section 4). This slightly alters the total arc tune and β functions. This fine matching is realized by constraining the total tune of the ring, to Qx/Qy = 66.28/66.31, and the 2.566 phase advance in the insertion (section 5), while performing iterative tunings of alternately the whole ring and the dispersion suppressor. The initial mismatch is small enough that usually 1 or 2 iterations are sufficient.

A slight loss of periodicity of the machine and a β-amplitude beating finally remains, which in the present case appears to be negligible in the horizontal plane, and about 0.3 m (sigma value) in the vertical plane (**Fig. 10**), which is conveniently small.

The change in the insertion tuning that results from this β matching is small enough that the detuning curves (**Fig. 6**), the peak β values (**Fig. 7**) and the optical functions (**Figs. 8,9**) are negligibly affected. The same remark is worth for the arc optical functions, while the arc tunes alternate from arc to arc between the phase advance values of 5.725 (odd arc) and 5.713 (even arc) in either plane.

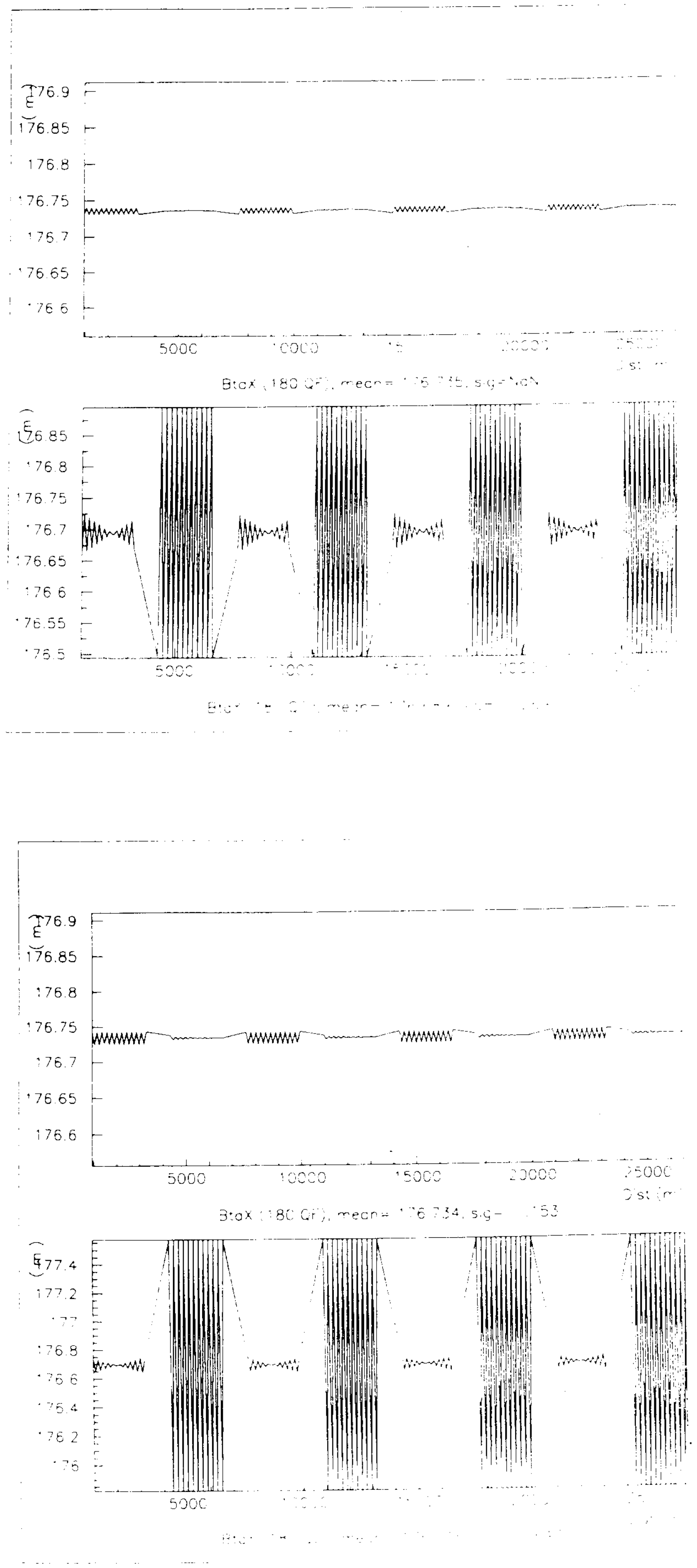


Fig. 10: Residual β beating along the symmetric ring
a) injection conditions (β*=6 m), b) collision conditions (β*=0.5 m)

8. OPTICS WITH TUNE SPLIT IN THE ARCS

A reduction of the effect of the a2 coefficient in the dipoles can be obtained by splitting the horizontal and vertical tunes. A tunability range Q_x - Q_y of up to ±2 units is foreseen.

The upper limit of ±2 units has been investigated thoroughly; it can be attained by matching the IR tune and Twiss functions with 17 gradients, namely, the 8 gradients of the two DS quadrupoles, the 6 gradients of the two outer triplets, and the 3 gradients of the two inner triplets connected in series. The constraints remain the same as in the standard case of equal integer tunes, as described in section 5.

However, the search for the optimum focusing is made difficult with the extreme tune split value of ±2, and also serious drawbacks appear, such as the strong sensitivity of the focusing to the longitudinal position of the quadrupoles. **Fig. 11** shows the strongly tossed shape of the quadrupole strengths of the insertion, when scanning over the range 0.5 m $\leq \beta^* \leq$ 11 m, in the split case Q_x/Q_y = 65.28/67.31. However, the corresponding optical functions behave well, over the full range 0.5 m $\leq \beta^* \leq$ 11 m, as can be observed in **Fig. 12**. The split tunes Q_x/Q_y = 64.28/66.31 and Q_x/Q_y = 66.28/68.31 have also been studied in detail and give similar results, as well for the (tossed shape of) the quadrupole strength scanning, as for the (well-behaved) optical functions.

The ±1 units tune split is attained by matching the IR tune and Twiss functions with 10 gradients, namely, by assuming antisymmetry with respect to the IP, as in the standard case of equal integer tunes. There is no special problem with the ±1 units tune split: the quadrupole strength scan is similar to the non spilt case (**Fig. 6**) as well as the Twiss functions (**Figs. 8, 9**). **Fig. 13** shows the β beating along the ring as induced by the tune split.

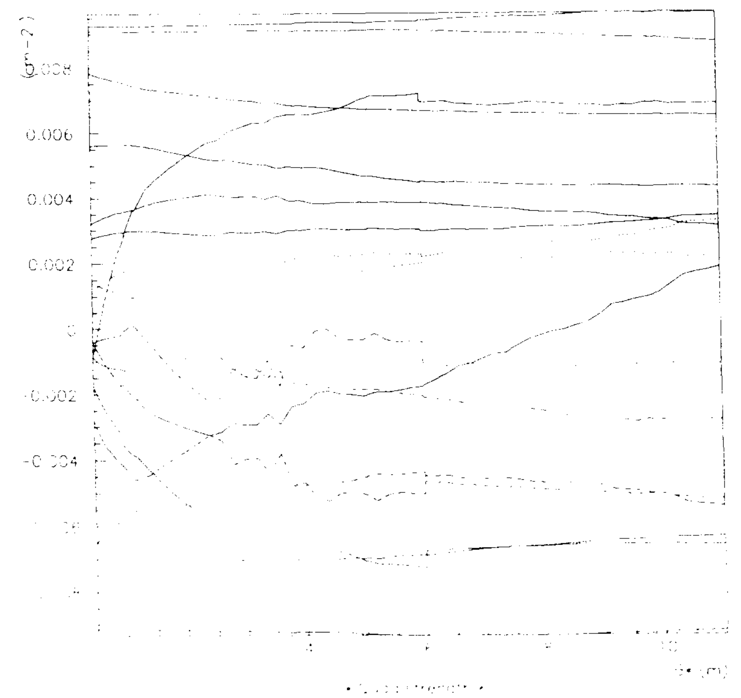
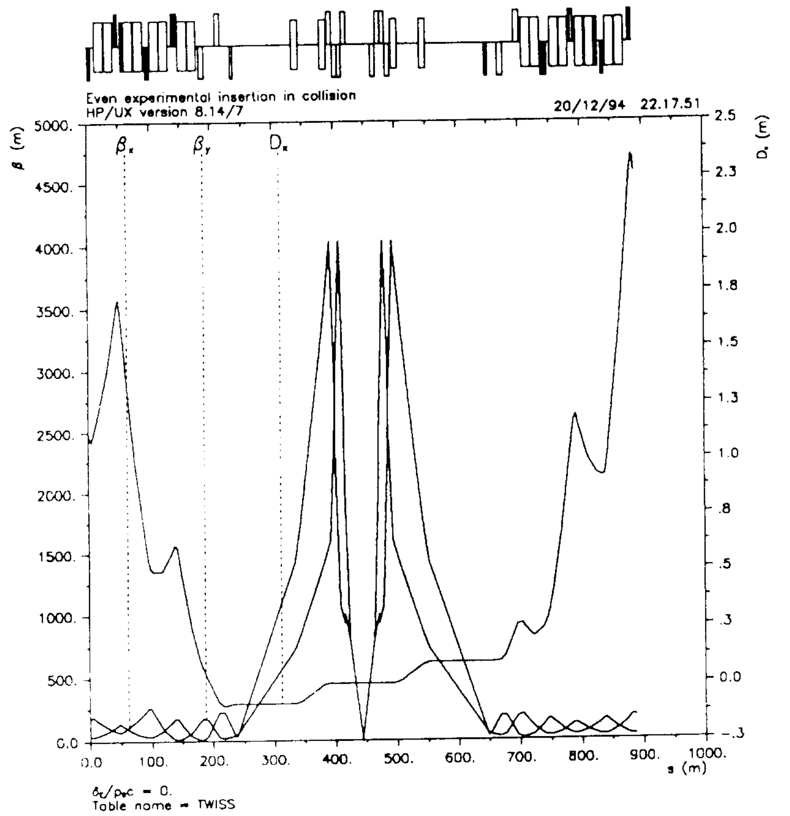


Fig. 11: Scan of the quadrupole strengths for an even type insertion (L*=21 m), over the range 0.5 m $\leq \beta^* \leq$ 11 m (Similar results are obtained for the odd insertion)



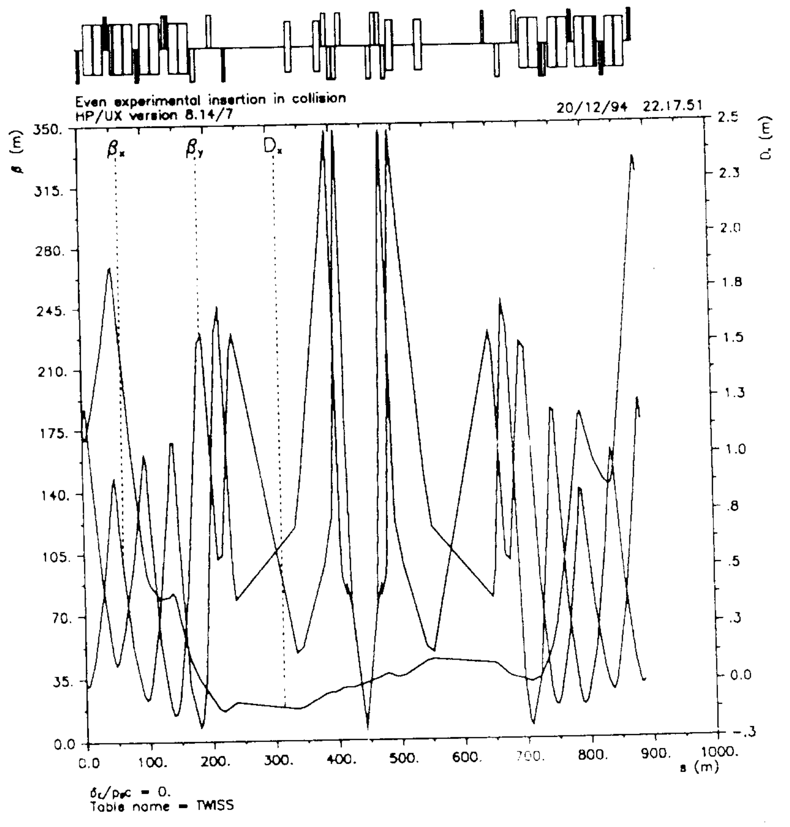


Fig. 12: Optical functions of the even insertion (L*=20 m) in the case of a ±2 tune split (Q_x/Q_y = 65.28/67.31)
upper frame: collision conditions, β* = 0.5 m
lower frame: injection conditions, β* = 6 m

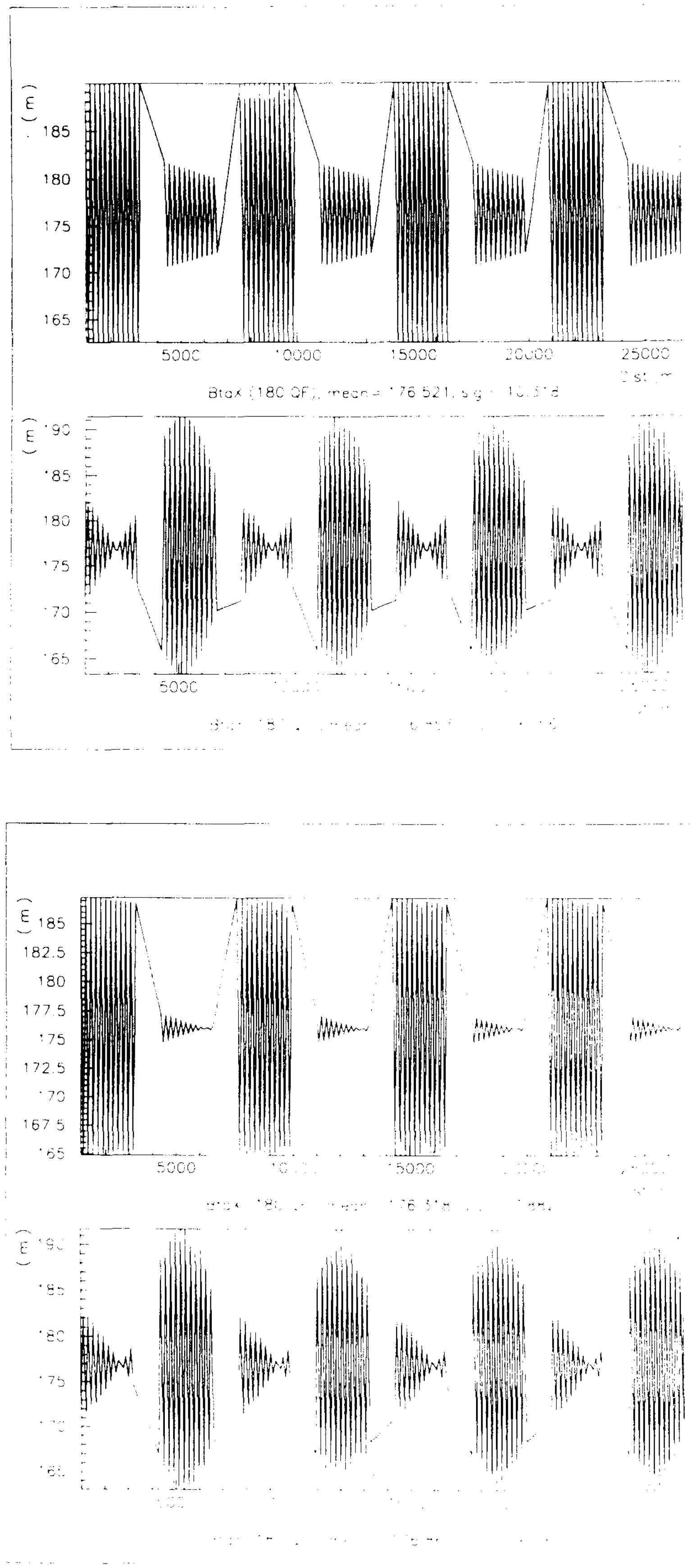


Fig. 13: x and y β beating along the ring, in presence of tune split
a) injection conditions (β*=6 m), b) collision conditions (β*=0.5 m)

9. TUNE SPLIT WITH PHASE TROMBONES

An alternative solution for a ±2 split tune working scheme, is to introduce a phase trombone in a dedicated IR free of physics experiments, e.g., in IR 4 (**Fig. 1**).

The specimen phase trombone described here extends over 528.238 m (that is, the extent of the even type LSS, see **Table 1**) and links at both ends to the last dipole of the regular DS (described in section 4), through adaptation half-cells. The trombone core is made of eight 54 m long cells plus one half-cell for antisymmetry, built up of pairs of 3.252 m long quadrupoles with 1.0 m spacing. The trombone is designed for a nominal phase advance $\Delta Q_x/\Delta Q_y=2$, and allows phase advances ranging arbitrarily between 3/1 and 1/3 by steps of 0.5 (e.g., 3/1, 2.5/1.5, 2/2, 2/3, etc.), with corresponding β_{max} values ranging from about 190 m to about 280 m. Three specimen of tune split focusing are displayed in **Fig. 14**.

From this design, an optics has been derived that allows the fine tuning of Qx and Qy.

To obtain ±2 units tune split, one can use the phase trombone which assures ±1 unit split, while the other ±1 unit can be assured by tune splits in the arcs, as described in the previous section.

Another possible scenario, still to be investigated, for reaching the range of ±2 units is to include two simplified phase trombones of ±0.5 unit each, in the optics of the two cleaning insertions IR 3 and IR 7, while still assuring the remaining ±1 unit by tune split in the arcs.

A general argument in favor of the scheme with phase trombones is that ±1 unit tune split in the arcs can be accommodated easily and in a clean way by a matching of the experimental IR's with only 10 quadrupole strengths, as described in the previous section.

10. ACKNOWLEDGMENTS

C. Rufer optimized the space occupancy in the regular cell. R. Ostojic made the insertion suited for the injection scheme from outside. and carefully checked the optical solutions presented here in view of optimizing the quadrupole lengths. The layout of the inner triplet is that of reference [7].

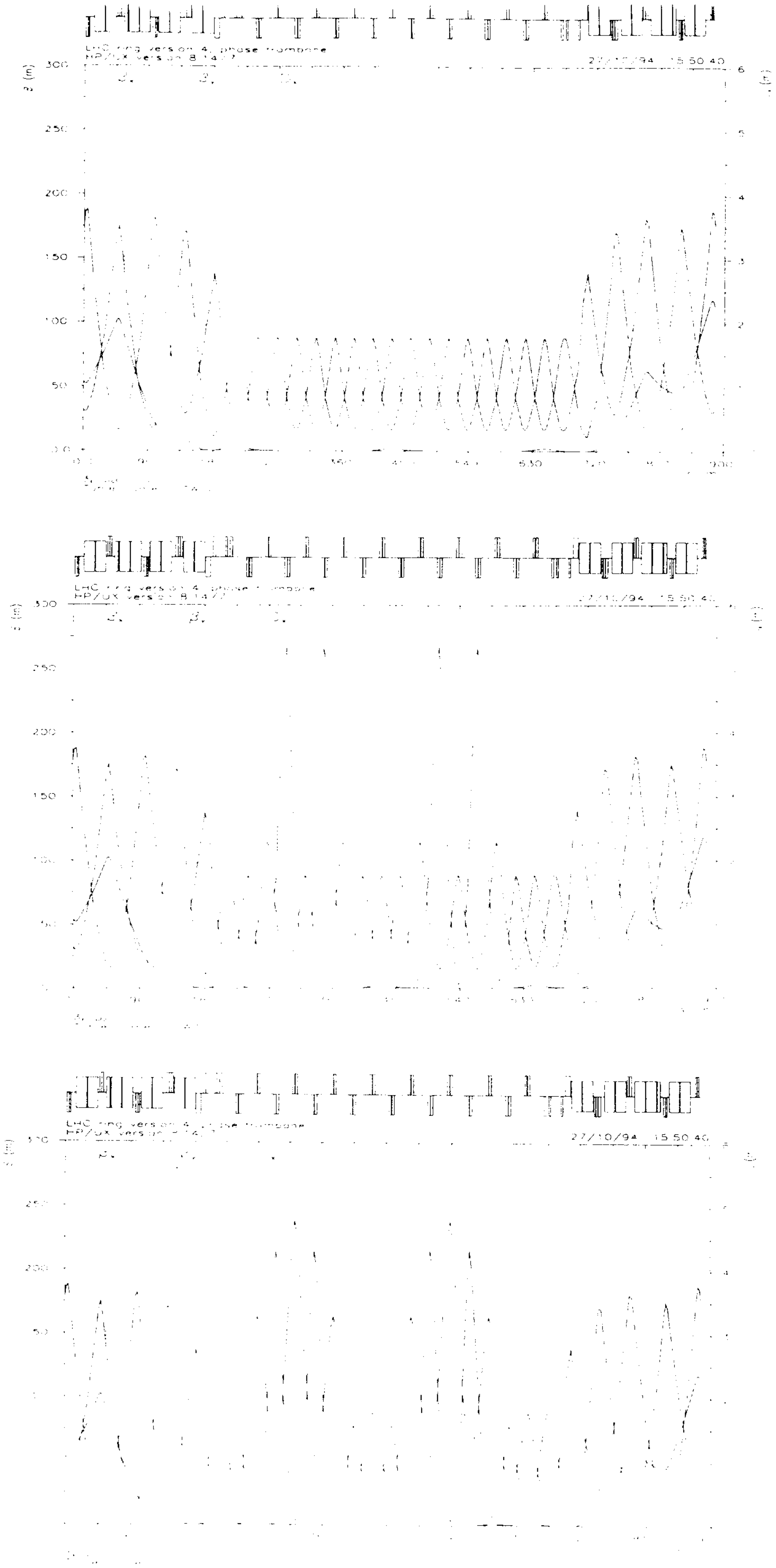


Fig. 12: Optical functions in the phase trombone, providing a phase advance $\Delta Q_x/\Delta Q_y$ of a) 2/2 (tune split=0), b) 2/3 (tune split=1), c) 1/3 (tune split=2)

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